Mesoanalysis of Bow Echo Environments during BAMEX

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ABSTRACT

One of the more significant forms of mesoscale convective organization is the bow echo. Although bow-shaped convective lines are relatively small in scale (20 – 120 km long), they can produce damaging straight-line winds over periods of several hours across swaths of several hundred kilometers. Bow echoes represent a challenge for operational forecasting and warning of severe weather. It is difficult to predict the severity of these systems, which often results in false severe weather warnings issued to the public.

The environments of bow echoes sampled on June 10, June 24, June 25/26, and July 4/5, 2003 during the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) were analyzed to determine differences associated with bow echoes that produce localized vs. widespread straight-line wind damage. Surface-based, Most Unstable, and Mixed Layer Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) were computed from environmental soundings. Bulk wind shear was also calculated for surface to 3 km (low-level) and surface to 6 km (deep layer) intervals for the four cases. In addition, an analysis of bow echo maintenance was performed by comparing the velocity representing the strength of the cold pool versus ambient low-level wind shear.

The results of this investigation indicated that the amount of CAPE and CIN can vary greatly in the environments preceding bow echoes. In addition, there was no significant difference in the amount of low-level or deep layer wind shear to contrast localized versus widespread straight-line wind damage cases. The results of this investigation will be useful to other scientists who are investigating different aspects of these four cases.

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I. INTRODUCTION

Convective storms occur in many forms, producing a large variety of severe weather and affecting areas ranging from a few kilometers (a small town) to hundreds of kilometers (several states). There are three basic convective storm types: ordinary cells, multiple cell systems, and supercells. The Bow Echo and Mesoscale Convective Vortices Experiment (BAMEX) focused on long-lived systems composed of multiple convective cells (http://www.mmm.ucar.edu/bamex/science.html).

One of the more significant forms of mesoscale convective organization is the bow echo (e.g., Fig 1). Bow-shaped convective lines are often associated with swaths of damaging straight-line winds and occasionally tornadoes that can pose a hazard to life and property. The initial stages of bow echo formation begin with a single to several convective cells that form into a line of precipitation. The appearance of mid-level cyclonic and anticyclonic “bookend” vortices at approximately 700 mb (3 km altitude) helps to create and intensify a rear-inflow jet. A rear inflow notch (RIN) seen in precipitation at the surface often signifies the location of descent for a strong rear-inflow jet from mid-levels (Figure 2). When the rear-inflow jet descends to the ground at the leading edge of the bow, it can create a swath of damaging surface winds. Although bow echoes are relatively small in scale (20 – 120 km long), they can produce damaging winds over periods of several hours across swaths of several 100 km (Weisman 2001).

Bow echoes are observed both as isolated convective systems and also within much larger convective systems, such as squall lines (usually North-South oriented lines of continuous thunderstorms). There are two basic patterns which favor the formation of bow echoes (Figure 3). A “warm season” pattern consists of a relatively weak synoptic stationary front. Bow echoes which develop along the boundary propagate north of, but parallel to, the stationary front and are generally seen only in the late spring and summer months. Relatively weak vertical wind speeds but extreme thermodynamic instability is associated with a “warm season” pattern. In contrast, a “dynamic” pattern, which is characterized by a strong low pressure system associated with very strong wind speeds and marginal instability, can produce bow echoes that are observed in all seasons (Johns and Hirt 1987).

Bow echoes represent a real challenge for operational forecasting and warning of severe weather. Although some bow echoes produce widespread significant severe weather, other bow-shaped convective lines fail to produce any severe weather. False alarms are often issued to the public for these latter systems. One of the motivations for BAMEX was to study how the production of severe weather in bow echoes is related to the larger scale environment of the convective system.

The inability to differentiate bow echoes that produce localized versus widespread wind damage could be the result of insufficient spatial and temporal samplings of the atmosphere. This research involves a mesoanalysis using higher resolution sounding data from BAMEX to examine the evolution of environments prior to bow echoes and an investigation of previously proposed conditions for bow echo maintenance.
Environment Evolution Prior to Bow Echo

The magnitude of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) available in the environment prior to a bow echo may be important in determining the severity of winds associated with it. CAPE is the amount of energy that a parcel can utilize on its upward ascent through the atmosphere. In contrast, CIN is the amount of energy required to lift a parcel to its level of free convection. Severe bow echoes are most often observed in environments with very high CAPE (2500 J kg\textsuperscript{-1}) and low CIN (< 25 J kg\textsuperscript{-1}) (Johns and Hirt 1987).

CAPE and CIN are calculated using temperature profiles plotted on thermodynamic skew-T diagrams (Figure 4). Currently, rawinsonde data are obtained from certain National Weather Service (NWS) offices twice daily at 00Z and 12Z. If weather conditions appear favorable for severe weather, additional temperature soundings are collected at 06Z or 18Z. Clearly, the atmosphere can change significantly over a 12 hour, or even 6 hour time span. For the four bow echo cases to be studied, a minimum of 25 soundings were released in the environment both prior to and after bow echo passage, giving a significantly higher resolution of sounding data. An analysis of BAMEX data collected from the environment immediately preceding a bow echo will document the environment evolution prior to bow echo events in order to differentiate environments that contribute to localized versus widespread wind damage.

Bow Echo Maintenance

One of the current theories for the formation of long-lived quasi-linear convective systems focuses on balance of the advancement of the associated outflow cold pool as compared to the strength of the opposing low-level environmental shear (Rotunno et al. 1988, referred to hereafter as RKW). Once a quasi-linear convective system, such as a bow echo, is established, interaction among the cells produces a nearly continuous region of rain-cooled outflow, known as a cold pool. If the cold pool advances too far out in front of the convective line, the updrafts will be cut off from environmental air that is necessary for the system to sustain itself. On the other hand, if the opposing low-level environmental shear is stronger than the circulation induced by the cold pool, the storm cannot maintain the upright tilt that is favorable for a strong, long-lived system (Rotunno et al. 1988) (Figure 6).

The environments of bow echoes sampled on June 10, June 24, June 25/26, and July 4/5, 2003 during BAMEX were analyzed to determine differences associated with bow echoes that produce localized vs. widespread straight-line wind damage. Surface-based, Mixed Layer (ML), and Most Unstable (MU) CAPE and CIN were computed from environmental soundings. Bulk wind shear was also calculated for surface to 3 km (low-level) and surface to 6 km (deep layer) intervals for the four cases. In addition, an analysis of bow echo maintenance was performed by computing a ratio of the cold pool strength to the ambient low-level wind shear. The wind speed and direction from the surface to 3 km was compared using rawinsondes released ahead of the bow echo with dropsondes released into the cold pool from the Lear jet. This allowed a comparison for the balance of the cold pool outflow with low-level shear.
II. METHODS

Four cases, June 10, June 24, June 25/26, and July 4/5, 2003 were identified for this study based on bowing reflectivity features in radar images from the WSR-88D network located in the BAMEX domain (425 nm range from Middle America Airport near St. Louis, MO). The cases were assigned categories based on damage reports from the Storm Prediction Center’s Index of Severe Thunderstorm Events web page (http://www.spc.noaa.gov/exper/archive/events/searchindex.html). The cases were separated into 2 categories: 1.) Localized straight-line wind damage (June 10 and June 25/26) and 2.) Widespread straight-line wind damage (June 24 and July 4/5).

Soundings were collected using two different methods: the Lear jet released dropsondes and the Ground Based Observing System (GBOS), which consisted of M-GLASS1, M-GLASS2, and the Mobile Integrated Profiling System (MIPS), which released rawinsondes. The research focused primarily upon values of CAPE/CIN and vertical wind shear, so the primary source of data from the BAMEX research products were soundings that measure temperature, dew point, and wind speed and direction at different levels of the atmosphere (http://www.joss.ucar.edu/cgi-bin/catalog/bamex/research/index). It was necessary to have a number of soundings both prior to and after the strongest convection associated with each bow echo to investigate proposed conditions for bow echo maintenance. The evolution of the environment prior to a bow echo was sampled primarily by M-GLASS and MIPS (when available) from stationary locations. The Lear jet mainly sampled the cold pool region by releasing dropsondes behind the bow echo.

For each bow echo case, isochrones of solid convective lines with maximum reflectivity >45dBZ were plotted for 2 or 3 hour intervals with the sites of dropsonde and rawinsonde releases. Next, images from individual WSR-88D radars were used to determine if soundings occurred ahead or behind the leading convective region of the bow echo.

For consecutive stationary rawinsonde releases by M-GLASS, the Rawinsonde Observation (RAOB) program was used to calculate surface based, most unstable (MU), and mixed layer (ML) CAPE/CIN values. The MU CAPE/CIN was evaluated using the level in the lowest 300 mb of the atmosphere that was associated with the greatest amount of CAPE. The ML CAPE/CIN was evaluated using an average of temperature and dew point information in the lowest 50 mb of the atmosphere. All calculations were made relative to above ground level (AGL) information. CAPE/CIN values were calculated using a standard dry bulb temperature rather than a virtual temperature base. In addition, CAPE values were calculated for 0-9km AGL because some of the soundings were terminated before reaching the Equilibrium Level.

The theory presented by RKW for bow echo maintenance was tested using soundings released ahead of the bow echo with those released into the cold pool with a time difference of <1.5 hours. The velocity representing the strength of the cold pool (Rotunno et al. 1988) was calculated using the following equation:

\[ c = (2\int_{-BL} B_t \, dz)^{1/2}, \]

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where $B_L = -g \Delta \Theta / \Theta_o$. $\Delta \Theta$ is the potential temperature deficit within the cold pool, $\Theta_o$ is the base-state potential temperature, and $c$ is the velocity representing the strength of the cold pool. The integration occurs over the depth of the cold pool as determined from a sounding. The value of $c$ was then compared with the amount of shear in the direction of bow echo propagation to determine how the observed bow echo states compare to the “optimal state” for quasi-linear convective systems proposed by RKW.

### III. RESULTS AND DISCUSSION

**June 10, 2003**

The target for the June 10, 2003 BAMEX case was a convective system which originated in southeast South Dakota/northeast Nebraska along and just ahead of an upper-level short wave trough and associated cold front. The system began with two tornadic supercells and propagated in a southeast direction along the border between Nebraska and Iowa where it later evolved into two distinct severe bow echoes. The first bow moved through the Sioux City, Iowa region between 02-04 UTC, and the second moved through the Lincoln, Nebraska region between 04-06 UTC. These two bow systems subsequently merged into one system, which continued to propagate southeast through Missouri.

This case was classified as a localized wind damage event. The SPC Severe Weather Reports recorded 10 wind damage reports for the first bow echo and 7 reports for the second. Although the region affected by wind damage was small, a damage survey conducted by Nolan Atkins and Jeff Trapp found F0 and limited areas of F1 damage in the regions where the reports originated (http://apollo.lsc.vsc.edu/bamex). The severity of straight-line wind damage is supported by a RIJ with wind speeds measuring up to 80 knots as reported by the NOAA P3 (www.joss.ucar.edu/bamex/catalog/missions.html).

**Evolution of Environment**

Figure 6 shows the location of the M-GLASS1 and M-GLASS2 vehicles which each released three rawinsondes to sample the evolution of the environment before the bow echo passed. The M-GLASS1 and M-GLASS2 vehicles remained stationary (with one exception when M-GLASS2 released a sounding at 0052 UTC and then moved farther south) so the evolution of the environment in time was documented at each location.

Figure 7 shows a comparison in the amount of surface-based, ML, and ML CAPE/CIN for both of the M-GLASS vehicles. For the soundings released from M-GLASS1, both the amount of surface-based and ML CAPE increased from 0248Z to 0354Z. However, at 0457Z the amount of surface-based and ML CAPE decreased, with slightly higher amounts of CAPE than CIN for the surface-based case, while the amount of CIN was greater than the amount of CAPE for the ML case. For the soundings released from M-GLASS2, for both the surface-based and ML cases, the amount of CIN was greater than the amount of CAPE and as time progressed, the amount of CIN continued to increase while the amount of CAPE continued to decrease.
In contrast to the stabilization of the atmosphere for parcels originating in the boundary layer, the MU case showed an increase in the amount of CAPE and a decrease in the amount of CIN in the environment immediately preceding the bow echo. For the soundings released from M-GLASS1, the amount of CAPE was initially greater than the amount of CIN at 0248Z and continued to increase while the amount of CIN decreased slightly. However, for the soundings released from M-GLASS2, at 0052Z the amount of CAPE (284 J/kg) was slightly smaller than the amount of CIN (309 J/kg). In contrast, the sounding released less than two hours later at 0243Z showed a dramatic increase in the amount of MU CAPE (1478 J/kg) and a decrease in the amount of MU CIN (48 J/kg). The next sounding showed a continuation of this trend with 1759 J/kg of MU CAPE and only 27 J/kg of MU CIN. Figure 8 shows the three M-GLASS2 soundings overlaid. An increase in the dew point at approximately 825 mb helps to explain the large differences in the amounts of MU CAPE between the 0052Z sounding and those taken at 0243Z and 0403Z. In fact, the parcels with the greatest MU CAPE in the atmosphere according to the M-GLASS2 0403Z sounding in Figure 9 were those that originated at 825 mb, where the elevated moist layer appeared.

The variability in the amounts of MU CAPE in the environments sampled by M-GLASS1 and M-GLASS2 suggests important differences in the environments through which the bow echoes propagated. Although the amount of MU CAPE increased as the bow echo approached the location of M-GLASS1, the highest amount of MU CAPE was 753 J/kg, less than half of the highest amount of MU CAPE measured at the location of M-GLASS2 (1759 J/kg). One could speculate that the variability in CAPE directly affected bow echo structure. M-GLASS1 was located near the cyclonic bookend vortex of the first bow echo whereas M-GLASS2 was located near the apex of the second bow echo. This could suggest that a maximum in CAPE along a linear system plays an integral part in increasing convection in the portion of the system that first begins to bow outward from the line.

**June 24, 2003**

The target for the June 24, 2003 BAMEX case developed from a cluster of supercells in northeast Nebraska, in a similar location where convection began for the June 10, 2003 case. The system evolved into a line echo wave pattern (LEWP) and finally into a bow echo that propagated eastward into northern Iowa/southern Minnesota and Wisconsin. Similar to the June 10, 2003 case, a double bow structure became evident by 0600Z but consolidated into a single larger bow echo system over a shorter time period (approximately 1 hour).

In contrast to the June 10, 2003 BAMEX case, this case was classified as a widespread straight-line wind damage event. The SPC Severe Weather Reports recorded 14 wind damage reports spanning 10 counties in northeast Nebraska and northwest Iowa. Although most of the damage was to trees, with few structures sustaining damage from the bow echo, the larger geographical area affected by wind damage classified this case as a widespread event.

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Evolution of Environment

Due to the requirements of the BAMEX GBOS team to redeploy farther south from its original position, the evolution of the environment over time from a stationary location was not available for this case. However, horizontal variability in the environment preceding a bow echo can be analyzed from a series of dropsondes released by the Lear jet as it flew from east to west on its approach to the bow echo. Figure 10 shows the location of the 6 soundings that were collected by the Lear jet during the time span of 0321Z to 0401Z.

Figure 11 shows the surface-based, MU, and ML CAPE and CIN for each of the 6 soundings from the environment prior to the bow echo. The values of CAPE and CIN represent not only the evolution of the environment over time, but also location, i.e. the sounding taken at 0321Z was farthest from the bow echo, while the sounding taken at 0401Z was closest to the bow echo. In contrast to the June 10, 2003 BAMEX case, both the surface-based and ML CAPE increase with time and proximity to the bow echo. Of interest is the comparison between the surface-based CAPE/CIN and the MU CAPE/CIN. Except for the first sounding, the amount of surface-based CAPE was slightly less (or in the case of the 0353 sounding, the same) as the amount of MU CAPE. Unlike the previous case, this suggests that the most unstable layer of the atmosphere is near the surface. In addition, the highest levels of surface-based (2763 J/kg), ML (2774 J/kg), and MU CAPE (2856 J/kg) calculated from the 0401Z sounding closest to the bow echo are values only from the LFC to 9 km. Due to the fact that the Lear jet flew at an altitude equivalent to approximately 300 mb, the BAMEX soundings often do not include the Equilibrium Level (EL). It is estimated that the total amount of surface-based CAPE was 4000+ J/kg for this case. The relatively high amounts of surface-based, ML, and MU CAPE coupled with low amounts of CIN may have been an important factor that distinguished between the widespread wind damage associated with this event and the localized wind damage associated with the June 10, 2003 BAMEX case.

June 25/26, 2003

The target for the June 25/26, 2003 BAMEX case was a broken line of convection with bowing segments observed in southwestern Iowa by mid-afternoon on June 25. Once established, the convective system moved eastward toward northern Illinois and southern Wisconsin, where convection slowly weakened and dissipated before reaching Lake Michigan. The SPC Severe Weather Reports recorded 18 wind damage reports spanning 7 counties in northern Illinois. Although this case recorded more wind damage reports than the June 24, 2003 case, the damage was limited to only 7 counties rather than the 10 counties reported in the previous case. Similar to the June 10 case, where damage was restricted to a limited area, this case was classified as a localized wind damage event.

According to the BAMEX Mission Summary for this case (joss.ucar.edu/bamex/catalog/missions.html), the two objectives for this mission were (1) to conduct a detailed study of the structure of the bowing segments which never developed into mature bow echoes and understand the physical processes that resulted in their formation and dissipation and (2) to better understand how the observed eastward weakening of the surface to 500 mb shear and decrease in CAPE may have contributed to
the observed collapse and forward spreading of the cold pools associated with the bowing segments of the linear convection.

**Evolution of Environment**

Figure 12 shows where two soundings were released each by M-GLASS1 and M-GLASS2 from stationary locations. Figure 13 shows the evolution of the environment with from these respective soundings. This case represents another example of the horizontal variability of the environment prior to bow echoes over short spatial distances. For the M-GLASS1 2243Z sounding, the amount of surface-based CAPE was equal to the amount of MU CAPE (783 J/kg), which means that the surface was the most unstable layer in the atmosphere. This is supported by the fact that ML CAPE was only 416 J/kg, which means that mixing in the lowest 50 mb of the atmosphere only decreased the amount of CAPE available for a parcel. For the next sounding taken at 0018Z, the amount of surface-based CAPE increased slightly and was again equal to the amount of MU CAPE (878 J/kg). However, the amount of ML CAPE has increased to 721 J/kg. This suggests that although the surface was still the most unstable layer in the lowest 300 mb of the atmosphere, mixing in the lowest 50 mb of the atmosphere could still yield similar values of CAPE.

The amount of CAPE available from the M-GLASS2 soundings may explain the short-lived nature of this localized wind damage event. Interestingly, the apex of a bowing line segment passed over M-GLASS2 instead of the M-GLASS1 location where higher amounts of CAPE were available. The M-GLASS2 2119Z sounding showed small amounts of CAPE available in the atmosphere, with the largest value equal to 520 J/kg of MU CAPE. However, in the 2220Z sounding, which was taken before the bowing line segments merged, there are large differences in the amounts of surface-based, ML, and MU CAPE. Surface-based CAPE was unable to be computed and the amount of ML CAPE (46 J/kg) differed greatly from the amount of MU CAPE (814 J/kg). Figure 14 shows the M-GLASS2 2220Z sounding which shows a cold pool from the surface to approximately 900 mb. This accounts for the fact that surface-based CAPE was unable to be computed and ML CAPE was very small. The much larger value of MU CAPE is due to the fact that the most unstable layer in the atmosphere is directly above the cold pool. The fact that a cold pool was evident in a sounding taken at 2220Z even before the bowing line segments merged supports the short-lived nature of this system. The appearance of a cold pool in a sounding released into the environment prior to a bow echo suggests that the strength of the cold pool is greater than the opposing ambient wind shear and signifies the weakening stage of the system.

**July 4/5, 2003**

The target for the July 4/5, 2003 BAMEX case was an organizing severe MCS in northern Indiana during the late afternoon of July 4. A derecho event the previous evening in Iowa which moved eastward into southern Wisconsin and Michigan and finally into the Ohio Valley in the early morning hours of July 4 established a surface boundary that contributed to subsequent convection. The derecho event produced gravity waves, evidenced by Lear dropsondes in central and eastern Iowa, which propagated
eastward to initiate new convection over northwestern Indiana (joss.ucar.edu/bamex/catalog/missions.html). Subsequent convection exploded in the environment with 6000 J/kg of CAPE and rapidly organized into a severe bow echo in northern Indiana. Once established, the bow echo propagated southeastward along the pre-existing boundary left by convection associated with the prior derecho event into western Ohio. By 0200Z, the system weakened and a gust front became clearly visible ahead of the line (see Figure 15).

This case was classified as a widespread straight-line wind damage event. The severe bow echo was characterized by 80 knot surface winds covering a large region of east-central Indiana and western Ohio. The SPC Severe Weather Reports recorded 55 wind damage reports throughout this region. An extensive ground survey of this event revealed pockets of F1 wind damage, consistent with the 80+ knot surface wind reports (http://apollo.lsc.vsc.edu/bamex).

**Evolution of Environment**

Similar to the June 24, 2003 BAMEX case, GBOS was deployed too far west to sample the environment in northwestern Indiana where convection organized into the bow echo. However, horizontal variability in the environment preceding a bow echo can be analyzed from a series of dropsondes released by the Lear jet as it made two passes ahead of the line (2146Z to 2205Z and 2242Z to 2306Z). Figure 16 shows the surface-based, MU, and ML CAPE and CIN for each of the 7 soundings from the environment prior to the bow echo.

Table 1 shows the averages and standard deviations for surface-based, ML, and MU CAPE and CIN as well as low-level (surface to 3 km) and deep layer (surface to 6 km) shear for all four cases analyzed. Of interest are the variations in the amount of CAPE associated with each case as well as the limited standard deviation of low-level and deep layer shear for all of the cases. This suggests that the amount of CAPE rather than the amount of shear present in the atmosphere prior to a bow echo event should be used as a determining factor in predicting the longevity and severity of the system. Unlike the June 24, 2003 BAMEX case, this case showed little horizontal variability in the environment preceding the bow echo. For all calculations, this case exhibited low amounts of CIN. For example, the largest amount of CIN is 83 J/kg based at the surface. In addition, there were high amounts of CAPE for all soundings taken in the environment prior to the bow echo. Of the four cases, the July 4/5 case exhibited the least amount of horizontal variability in terms of CAPE. The average MU CAPE was 1562 J/kg with a standard deviation of 145 J/kg for the 7 soundings released into the environment. Although the average MU CAPE (2220 J/kg) for the June 24, 2003 case was higher than the average for the July 4/5, 2003 case, there was also greater horizontal variability as seen in the standard deviation of the June 24, 2004 MU CAPE (405 J/kg). Although the June 24, 2003 case was classified as a widespread wind damage event, the July 4/5 case produced significantly more damage. A greater homogeneity in the environment associated with the July 4/5 bow may explain the increased severity of the system.
Bow Echo Maintenance and RKW Theory

Figure 17 shows the average ratio of $c$ (velocity representing the strength of the cold pool) to $\Delta u$ (opposing low-level ambient wind shear) for 9 pairs of soundings. The classification stages of developing, mature, and weakening were decided subjectively by looking at radar images of the bow echo at the time of the cold pool sounding. It should be noted that the average for the developing stage is actually from only 1 pair of soundings.

A positive trend in the ratio of $c$ to $\Delta u$ correlates well with previous theory that during the life of a linear convective system the strength of the cold pool increases until it ultimately causes the destruction of the system’s structure. According to RKW theory, in the developing stage of a linear system, $c < \Delta u$. However, the results from the graph indicate that at the developing stage of a bow echo $c \sim \Delta u$. Rather than disproving RKW theory, these results act to reinforce it. The theory for strong, long-lived squall-lines presented by Rotunno et al. 1988 applies to linear systems. In its developing stage, a bow echo resembles a linear system so the ratio for the developing stages of a bow echo agrees with RKW theory. Of interest is the average ratio for the mature stage of a bow echo’s lifetime. According to the results, in its mature stage the strength of the cold pool is approximately one and a half times as strong as the opposing low-level wind shear. Since some bow echoes can maintain their structure for several hours, the imbalance of the cold pool to ambient wind shear suggests that there must be other factors contributing to the maintenance of bow echo structure. In this respect, bow echoes would be better defined as quasi-linear rather than linear convective systems. Finally, during the weakening stages of a bow echo’s lifetime the strength of the cold pool increased to nearly twice that of the opposing low-level wind shear. Although a larger set of cases should be analyzed to determine if these ratios are accurate, the results of this study suggest that a greater understanding of the balance between the cold pool of a bow echo and the opposing low-level ambient wind shear is necessary.

IV. CONCLUSION

The results of this investigation indicated that the amount of CAPE and CIN can vary greatly in the environments preceding bow echoes. The variability in levels of CAPE along a developing linear system could play an integral part in increasing convection in the portion of the system that first begins to bow outward from the line.

Relatively high amounts of surface-based, ML, and MU CAPE coupled with low amounts of CIN may be an important factor that distinguishes between localized and widespread wind damage events. Moreover, greater homogeneity with relatively large values of CAPE (1500+ J/kg) may characterize particularly severe bow echoes.

In addition, there was no significant difference in the amount of low-level or deep layer wind shear to contrast localized versus widespread straight-line wind damage cases. This suggests that the amount of CAPE rather than the amount of wind shear present in the environment prior to a bow echo event should be used as a determining factor in predicting the longevity and severity of the system.
Figure 1. Example of a bow echo that covers several counties on radar. Areas of red denote heaviest precipitation, followed by areas of yellow. The large area of green behind the bow echo denotes stratiform rain.
http://www.skywarn.ampr.org/radar2.htm

Figure 2. A typical evolution of a bow echo that produces strong downbursts and damaging winds at the surface. Note the appearance of the rear inflow notch (RIN) behind the apex of the bow and the “bookend” vortices which become evident in Diagram C (Fujita 1978).
Figure 3. Two synoptic patterns which favor the formation of bow echoes. The “warm season” pattern (top), which exhibits a relatively weak synoptic stationary front, is confined almost entirely to late spring and summer. The “dynamic” pattern (bottom) indicates a strong low pressure system, where bow echoes are observed in all seasons. Gray areas indicate regions most likely affected by damaging straight-line winds during bow echo lifetime (Johns and Hirt 1987).

Figure 4. An example of a skew-T diagram with plotted values of temperature and dew point. The blue area is proportional to the magnitude of CIN and denotes where the parcel is cooler than its environment. The red area is proportional to the magnitude of CAPE and denotes where the parcel is warmer than its environment and will ascend until it becomes cooler than its environment at the Equilibrium Level.
Figure 5. Schematic diagram showing how a buoyant updraft may be influenced by wind shear and/or a cold pool. (a) With no shear and no cold pool, the axis of the updraft produced by the thermally created, symmetric vorticity distribution is vertical. (b) With a cold pool, the distribution is biased by the negative vorticity of the underlying cold pool and causes the updraft to lean back over the cold pool. (c) With shear but no cold pool, the updraft leans downshear. (d) With both a cold pool and shear, the two effects negate one another, and allow for an erect updraft and long-lived storm. [From Rotunno et al. (1988)]
Figure 6. Isochrones of solid convective lines with maximum reflectivity > 45 dBZ at three hour intervals overlaid with Lear jet (dropsonde) and GBOS (rawinsonde) locations for the June 10, 2003 BAMEX case.
Figure 7. A comparison of the amount of surface-based, Most Unstable (MU), and Mixed Layer (ML) CAPE/CIN from June 10, 2003 for both of the M-GLASS vehicles. Data for M-GLASS1 appears at the left, while M-GLASS2 appears at the right. The top graphs are for surface-based calculations, the middle graphs for ML calculations, and the bottom graphs for MU calculations. Values of CAPE (red) are from the LFC to 9 km AGL.
Figure 8. Overlaid soundings for the 3 rawinsondes released on June 10, 2003 by M-GLASS2. Note the increase in the dew point from the 0052Z sounding to the 0243Z and 0403Z soundings.

Figure 9. M-GLASS2 0403Z sounding with MU CAPE/CIN plotted. The most unstable layer in the atmosphere occurs at approximately 825 mb which coincides with the increase in dew points at elevated levels.
Figure 10. The location of the 6 soundings that were collected by the Lear jet during the time span of 0321Z to 0401Z during the June 24, 2003 BAMEX case.
Figure 11. Surface-based, MU, and ML CAPE/CIN for each of the 6 soundings released into the environment prior to the bow echo by the Lear jet during the June 24, 2003 BAMEX case.
Figure 12. Isochrones of solid convective lines with maximum reflectivity > 45 dBZ at two hour intervals overlaid with Lear jet (dropsonde) and GBOS (rawinsonde) locations for the June 25/26, 2003 BAMEX case.

Figure 13. Evolution of the environment prior to the bow echo on June 25/26, 2003. M-GLASS1 data appears at the top, while M-GLASS2 data appears beneath it. Each graph contains values of surface-based (left), ML (middle), and MU (right) CAPE/CIN.

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Figure 14. The June 25/26, 2003 2220Z M-GLASS2 sounding shows a cold pool from the surface to approximately 900 mb. This accounts for the fact that surface-based CAPE was unable to be computed and ML CAPE was very small. The much larger value of MU CAPE is due to the fact that the most unstable layer in the atmosphere is directly above the cold pool.

Figure 15. 0208Z July 5, 2003 Cincinnati, OH radar WSR-88D radar image which clearly shows a gust front (5 dBZ hemi circle on the southern border of Ohio) ahead of weakening bow echo.
Figure 16. Surface-based, ML, and MU CAPE/CIN for each of the 7 soundings released from the Lear jet into the environment prior to the bow echo on July 4, 2003.
Table 1. See attached link

![Cold Pool Strength to Low-level Shear Average Ratios](image)

Figure 17. Average ratio of c (velocity representing the strength of the cold pool) to \( \Delta u \) (opposing low-level ambient wind shear) for 9 pairs of soundings collected during BAMEX to test RKW theory. The classification stages of developing, mature, and weakening were decided subjectively by looking at radar images of the bow echo at the time of the cold pool sounding.
References


